UNCLASSIFIED

AD NUMBER
AD596288
CLASSIFICATION CHANGES
TO: **unclassified**
FROM: **confidential**
LIMITATION CHANGES
TO: **Approved for public release; distribution is unlimited.**
FROM: **Distribution authorized to DoD and DoD contractors only; Foreign Government Information; NOV 1972. Other requests shall be referred to British Embassy, 3100 Massachusetts Avenue, NW, Washington, DC 20008.**
AUTHORITY
DSTL ltr dtd 12 Dec 2006; DSTL ltr dtd 12 Dec 2006

THIS PAGE IS UNCLASSIFIED

U.K. CONFIDENTIAL

33/72

MINISTRY OF DEFENCE

ROYAL

ARMAMENT RESEARCH AND DEVELOPMENT

ESTABLISHMENT

R.A.R.D.E. MEMORANDUM 33/72

The spalling of armour plate and the influence of backing liners

(title RESTRICTED)

W M Evans, Ph D, D Sc

Fort Halstead
Kent

November
1972

U.K. CONFIDENTIAL

This Document was Graded
CONFIDENTIAL
at the 274 th meeting of the R.A.R.D.E
Security Classification Committee

RELEASE CONDITIONS FOR OVERSEAS DISTRIBUTION

A

1. THIS INFORMATION IS RELEASED BY THE UK GOVERNMENT TO THE RECIPIENT GOVERNMENT FOR DEFENCE PURPOSES ONLY.

2. THIS INFORMATION MUST BE ACCORDED THE SAME DEGREE OF SECURITY PROTECTION AS THAT ACCORDED THERETO BY THE UK GOVERNMENT.

3. THIS INFORMATION MAY BE DISCLOSED ONLY WITHIN THE DEFENCE DEPARTMENTS OF THE RECIPIENT GOVERNMENT AND TO ITS DEFENCE CONTRACTORS WITHIN ITS OWN TERRITORY EXCEPT AS OTHERWISE AUTHORISED BY THE MINISTRY OF DEFENCE. SUCH RECIPIENTS SHALL BE REQUIRED TO ACCEPT THE INFORMATION ON THE SAME CONDITIONS AS THE RECIPIENT GOVERNMENT.

4. THIS INFORMATION MAY BE SUBJECT TO PRIVATELY-OWNED RIGHTS.

B

1. THIS INFORMATION IS RELEASED BY THE UK GOVERNMENT TO THE RECIPIENT GOVERNMENT FOR DEFENCE PURPOSES ONLY.

2. THIS INFORMATION MUST BE ACCORDED THE SAME DEGREE OF SECURITY PROTECTION AS THAT ACCORDED THERETO BY THE UK GOVERNMENT.

3. THIS INFORMATION MAY BE DISCLOSED ONLY WITHIN THE DEFENCE DEPARTMENTS OF THE RECIPIENT GOVERNMENT AND TO THOSE NOTED IN THE ATTACHED LIST, EXCEPT AS OTHERWISE AUTHORISED BY THE MINISTRY OF DEFENCE. SUCH RECIPIENTS SHALL BE REQUIRED TO ACCEPT THE INFORMATION ON THE SAME CONDITIONS AS THE RECIPIENT GOVERNMENT.

4. THIS INFORMATION MAY BE SUBJECT TO PRIVATELY-OWNED RIGHTS.

C

1. THIS INFORMATION IS RELEASED BY THE UK GOVERNMENT TO THE RECIPIENT GOVERNMENT FOR DEFENCE PURPOSES ONLY.

2. THIS INFORMATION MUST BE ACCORDED THE SAME DEGREE OF SECURITY PROTECTION AS THAT ACCORDED THERETO BY THE UK GOVERNMENT.

3. THIS INFORMATION MAY BE DISCLOSED ONLY WITHIN THE DEFENCE DEPARTMENTS OF THE RECIPIENT GOVERNMENT, EXCEPT AS OTHERWISE AUTHORISED BY THE MINISTRY OF DEFENCE.

4. THIS INFORMATION MAY BE SUBJECT TO PRIVATELY-OWNED RIGHTS.

D

5. THIS INFORMATION IS RELEASED FOR INFORMATION ONLY AND IS TO BE TREATED AS DISCLOSED IN CONFIDENCE. THE RECIPIENT GOVERNMENT SHALL USE ITS BEST ENDEAVOURS TO ENSURE THAT THIS INFORMATION IS NOT DEALT WITH IN ANY MANNER LIKELY TO PREJUDICE THE RIGHTS OF ANY OWNER THEREOF TO OBTAIN PATENT OR OTHER STATUTORY PROTECTION THEREFOR.

6. BEFORE ANY USE IS MADE OF THIS INFORMATION FOR THE PURPOSE OF MANUFACTURE THE AUTHORISATION OF THE MINISTRY OF DEFENCE, D SALES (SALES 5a (A)), ST. CHRISTOPHER HOUSE, SOUTHWARK STREET, LONDON S.E.1 MUST BE OBTAINED.

R.A.R.D.E.
Printing Section

CONFIDENTIAL

2

MINISTRY OF DEFENCE

ROYAL ARMAMENT RESEARCH AND DEVELOPMENT ESTABLISHMENT. GB Brit.

6

RARDE MEMORANDUM 33/72

3

The spalling of armour plate and the influence of backing liners

(title RESTRICTED)

W M Evans, et al Ph D, D Sc (Consultant to RARDE)

4

5 - Nov. 1972
7 -
8c 41, 42

Summary

This note examines theoretically the influence of backing liners, such as Perspex and Tufnol, on the spalling of armour plate under attack, particularly by hollow-charge jets. Very little supporting experimental work has been undertaken but the report suggests that relatively thin liners can significantly reduce or suppress spalling, with consequent reduction in behind-plate lethality. (If the liners are thick, a further reduction in lethality by spall absorption in the backing material can occur; this is not analysed in the note). Experimental work is needed to optimise this type of improved composite armour. The report also indicates possible warhead modifications to combat such improvements.

Approved for issue:

W H Coulthard, Deputy Director (1)

CONFIDENTIAL

IMPORTANT

This document should be returned to the Reports Officer, Royal Armament Research and Development Establishment, Fort Halstead, Sevenoaks, Kent. when no longer required

INITIAL DISTRIBUTION

Internal

No 1	Director
2	Deputy Director (1)
3	Deputy Director (2)
4	SMO
5	Hd/AP
6	Hd/EM
7	Hd/ET
8	Hd/GR
9	Hd/MA
10	S/AP1
11	S/EM1
12	S/ET2
13	S/MA2

External (UK)

14	Chief Scientist (Army)
15	DG/ERP/B
16	DGRW
17	DGW(A) St Christopher House
18	ACGS (OR) Main Bldg
19	MVEE MOD(PE) Chobham Lane, Chertsey, Surrey (Attn Technical Services)
20	Secretary, OB
21	MOD Library (C&A) Old War Office Bldg
22	AWRE Aldermaston, Berks
23	DRIC - for retention

Overseas (through DRIC)

24	BDSW (R&D) (Attn Director of Munitions)
25	BDLS (Army) Ottawa
26-28	Canada - CFHQ for DCENG Technical Library
29-32	- Def Res Board
33	- CDLS
34	Australia - AAS (UK)
35-39	- Dept of Supply

Overseas (through DRIC) (Continued)

40 Australia	-	RAAF Overseas HQ London
41-55 USA	-	ONR (London)
56	-	Assist Sec of Def (Dep DDR&E)
57	-	Defense Documentation Center, Cameron Station, Alexandria, Va 22314
58-62	-	US Army Standardization Group, UK

Stock

63-67

Introduction

This short study outlines some of the simpler qualitative aspects of shock propagation in armour materials and the way interfaces and free surfaces influence fracture and spalling. A study in detail of this overall complex subject is not warranted at this stage since what is aimed at is a clarification of the mechanism of spalling in armour when attacked by jets with the special aspect of the observed suppressing influence on post-perforative fragmentation of suitable materials used as linings or backings to the rear face of the armour. This is of importance because of the contribution of fragmented spall to lethal effects beyond the defeated armour. It suffices to consider the elements of the problem in terms of propagation in the armour(s) of plane shocks as can be generated by explosive detonations or by flying plates on impact, and the way spalls are produced when such shocks are reflected from a free surface or from that surface when it forms an interface with another material. The conclusions drawn from this simplified procedure are in principle those applicable to spalling produced by jet action. The more important guides towards methods of increasing spalling in attack or suppressing spalling in defence may then be indicated. The attendant complex problem of spall break-up and projection is outside the scope of this brief study.

1. Shock formation and propagation

In the propagation of a simple form of compression pulse the high pressure elements travel faster than the lower pressure elements so that the front of the pulse becomes steeper with distance propagated eventually becoming infinitely steep to form a shock front. Conversely in a rarefaction wave (pressure decreasing) elements spread out with distance propagated and the front becomes less steep. The influence of low intensity shocks in materials that yield and flow can be explained by elasto-plastic mechanisms of behaviour. For high intensity shocks behaviour can be largely accounted for by hydrodynamic processes; and it is in this category that this study is concerned.

The properties on either side of the shock front are represented by the Rankine Hugoniot relationships which can be expressed as

$$U^2 = V_o^2 \frac{(P-P_o)}{V_o-V} \qquad (1)$$

$$u = \frac{P-P_o}{\rho_o U} \qquad (2)$$

$$E-E_o = \tfrac{1}{2}(P+P_o)(V_o-V) \qquad (3)$$

where P = pressure, V = specific volume, E = specific internal energy and U,u = shock and particle velocity, respectively. Subscript o refers to conditions in front of the shock; unsubscripted to those behind.

2. Wave Interactions

a. Fracture and spalling in single phase materials

One dimensional wave propagation, reflection and interaction can be represented in descriptive form by Fig 1. Fig 1(a) shows in time/distance form shock propagation in a single phase material. The attenuating influence of the dispersive rarefaction wave IH is seen in the way the shock AC falls in velocity. At the free surface C in the material (or at the interface between the material and another material of lower shock impedance (see later)), the shock is reflected, as a dispersive rarefaction wave. The surface drops abruptly to zero pressure but acquires a decelerated motion CD of about twice the incident particle velocity in the incident wave. At a stage in the interaction between the incident and reflected wave the induced state of tension in the material may develop sufficiently to cause fracture. In three-dimensional plane wave propagation the material between the plane of fracture and the free surface acquires the shock momentum trapped in it and hence may be induced to separate with appropriate velocity from the parent body. Fig 1(b) shows the process in terms of changing shock profile with propagation and reflection.

b. Fracture and spalling in polymorphic materials

In single phase materials the Hugoniot relationship of P with V can be represented by the dotted smooth curve in Fig 2. In polymorphic materials however no such smooth transitions occur. For example, in iron and most steels, which are of particular concern, the transition from the lower pressure range xy to the higher pressure range yz exhibits a discontinuity at y. Work carried out at AWRE and in the States has revealed that in the pressure range yz (y ~ 130 kb, z ~ 330 kb. 1 kb = 6.475 tons per sq in) phase changes are induced with consequent changes in propagation. It can be shown and has been experimentally observed that pressures above z are transmitted as a single shock wave but pressures below z, in the region of mixed phases zy are transmitted as two shock waves, the one of higher velocity corresponding to line xyz (xy considered linear), the other of lower velocity to line yz' of magnitude depending on the position of z'. A simplified descriptive outline of the process of shock propagation, reflection and interface reaction is shown in Fig 3 (a, b) for comparison with Fig 1 (a, b). The single shock AB at pressures above z in Fig 2 separates into two, BC and BE when the pressure drops below z. As the pressure is further reduced from about 180 kb to that at y, the rarefaction causing the expansion in this region is affected such that elements in it of higher pressure travel more slowly than those of lower pressure so that a shock develops connecting the two states above and below y. This pressure decreasing shock is called a negative shock, IK. For fair lengths of travel both negative shock and the slower shock, BE, become degraded by attenuation. But if the material is of short length and ends in a free surface the faster shock reflects at the free surface, C, as a rarefaction wave reducing the pressure to zero without inducing tension since the incident pressure is uniform. Interaction with the slower shock creates the shock ED and the rarefaction EL, the shock

separating into two if the pressure is at or near the transition point y. The rarefaction EL interacts with the incident rarefaction wave IH and a negative shock LM is developed as the elements of the wave reach the pressure in the vicinity of y. Thus two negative shocks approach each other. When they collide the material suffers instantaneous tension, Fig 3(b), which far exceeds the fracture stress in that region so that fracture occurs in a very narrow zone, the surfaces displaying a smooth appearance in contrast to the rough crystalline appearance and thinner spalls usually produced in single phase materials. These features with others, particularly associated dark-zone effects, can be accounted for only on the basis of the preceding description.

Very high intensity shocks in single phase materials can cause fracture by a disintegrating action as can be deduced from the rather wide zone and the rough and jagged appearance of the surfaces of separation. The same cohesive resistance to surface separation occurs in polymorphic materials under very high intensity shocks but as has been stated the zones are narrow and the surfaces smooth. At comparatively low shock intensities fracture is usually of a ductile nature. Clearly, stress intensity, stress gradient and time of application must be important factors in the way fracture is initiated and propagated. Critical fracture stresses are deduced to be some 3 to 8 times the static tensile strength of the material, the sharper the shock and the lower the static strength of, for example treated steels, the higher the factor.

3. Wave interactions at an interface

a. Incident, reflected and transmitted waves

The preceding descriptive outline of shock propagation and interaction indicates the complexities involved in even the simplest interpretation of practical situations. Detailed analysis of a quantitative nature is possible within limits, but is not warranted in the present requirement. It suffices in this study to simplify the procedure to that in which the shock is in single phase materials (or is at pressures in polymorphic materials below those that induce phase transformations), is of triangular pressure/wave length profile, suffers no attenuation and is of constant velocity both in its incident and reflected forms.

A shock transmitted across an interface - the boundary of separation between two different materials, can be represented as in the manner of Fig 1(a) for a simple material ending in a free surface, by the time/distance diagram, Fig 4(a). U_i, U_t, and U_r are the respective velocities (assumed constant) of the incident, transmitted and reflected waves. The strengths of the waves are determined by the conditions that the pressure P and the particle velocity u, must be continuous across the interface, so that $P_t = P_r$ and $U_t = U_r$. From equations (1) to (3) the reactions involved can be represented by a P,u diagram, Fig 4(b) for three materials L, M, N of decreasing order of impedance ($\rho_0 U$). If the incident shock strength in M is denoted by the point a, the intercepts at b and c of the image of the curve M through a with the curves L and M give the P,u values acquired across the respective interfaces. The points of intersection satisfy the conditions of continuity and are solutions to the state of shock at the interfaces. It is seen that for interface M,L the reflected wave in M is in compression. For interface ~~M,N the reflected wave is in rarefaction.~~

A great deal of work has been carried out to determine experimental P,u values for a large number of metals and non-metals. Provided the pressures do not exceed certain values, the P,u relationships are almost linear in form for most serviceable materials. Substitution in equations (1) to (3) lead to quantitative Hugoniot relationship of P with V/V_o to which are fitted empirical equations of state easier to use in practice.

b. Fracture

The resultant attenuating wave profile in a material system MN (where reflection is in rarefaction) is in essence depicted in Fig 1(b) for a free surface. If now the simpler more convenient but less accurate triangular non-attenuating shock is assumed and if in the first instance the material M ends in a free surface, reflection there must satisfy the conditions of continuity. Fig 5(a) which is Fig 1(a) appropriately simplified, conveys the time/distance sequence of propagation. During the phase of reflection the pressure falls to zero at the free surface, which acquires a velocity of about twice the particle velocity in the incident wave (intercept d in Fig 4(b)). The reflected wave is therefore in tension, balancing at the free surface the decreasing pressure (or stress) in the incident wave, of maximum value OC, Fig 5(b). After a propagation increment AA' = OO' (with $U_i = U_r$), the tension wave is O'CC'O and the resultant wave profile is indicated by A'BO'FO (dotted lines). This simplified form can be compared with that in Fig 1(b). Thus the material at O' is subjected to stress σ = −CO' + O'B = O'F and when $\sigma \geqslant \sigma_F$ the dynamic fracture stress of the material, fracture occurs there in the manner first reported by Hopkinson. If the dynamic fracture is known the position of the fracture is easily determined. More than one fracture may occur since the fracture zone on separation becomes itself a free surface from which the tail of the wave is reflected. The number and location of fractures depend on the shock profile and the critical fracture stress σ_F, and are conveniently obtained as illustrated in Fig 5(c) for two fractures situated at distances $\frac{l_1}{2}$ and $\frac{l_1 + l_2}{2}$ from the free surface at o.

For plane wave propagation the first spall of unit area and of length $\frac{l_1}{2}$ is endowed with the momentum proportional to the area OBB'C, and the second spall of unit area and of length $\frac{l_2}{2}$ has the momentum proportional to the area BDD'B', that is to $\frac{(OC + BB')}{2} \frac{OB}{U_i}$ and $\frac{(BB' + DD')}{2} \frac{DB}{U_i}$ respectively. Per unit length the momentum of spall decreases with distance from the free surface, so that provided the length of the material > wave length the nearer the fracture to the free surface, the greater is the velocity of the projected spall.

If material M buts on to material N of lower impedance Fig 6(a) the pressure at the interface drops from a to c and the wave reflected is in rarefaction, Fig 6(b). Continuity conditions are satisfied by the tension wave sent back into M of peak value OC − oB = BC. Thus in Fig 6(c) the incident wave OAC is reflected in tension as the image of the wave OAX

where OX = BC in Fig 6(b). After an increment in the propagation equal to AA' = OO' and provided material N is at least of length x fig 6(a), such that the wave reflected from its free surface arrives at the interface at the same time (or after) the tail of the incident wave arrives there, that is $\frac{2x}{U_N} \geq \frac{OA}{U_M}$, the excess tension O'X − O'F may be $\geq \sigma_F$. Fracture then occurs. The number and position of fractures are obtained simply as before. Fig 6(d) shows the incident and reflected wave profiles OAC and OAX respectively. Illustrated are three fractures if M ends in a free surface (intercepts 1, 1,1) but two fractures if M ends in an interface with N (intercepts 2,2).

If the length x of material N is such that $x < \frac{U_N}{U_M} \cdot \frac{OA}{2}$, the wave reflected from the free surface of N on arrival at the interface induces separation (u at intercept e > u at intercept d, Fig 6(b)) and the pressure there reverts to free surface zero pressure. Fig 7(a) illustrates the process. The reflected tension wave in M is, as before, of peak value O'X = OX = OC−OB, which is of length x, on reflection at the free end arrives at the interface, the pressure OX' there at that time immediately falls to zero so that the balancing tension for continuity jumps from OX' to OC'. After a further increment of propagation A'A'' = O'O'' the tension profile is shown by OO''XC'C'' where it is seen that the peak tension is now in the tail QC', Fig 7(b). Depending on the length of N the tension QC' can be greater, equal or less than the front O''X. When in the propagation the peak tensions exceed the compression by the amount σ_F fracture(s) occur. As before the number and position of fractures are obtained from Fig 7(c), though care must now be taken in deducing the sequence of fractures in position and time, since these depend on the time at which the interface pressure reverts to zero. After the first fracture (induced either by the front O''X and/or QC'') the creation of the free surfaces there lead to the possibility of further fractures either, or both, in the parent body of M or even between an already formed fracture and the interface.

Intercepts (1,1,1), (2) and (3,3) respectively denote the positions of fractures when M ends in a free surface and when N is long or short, that is, for x = 0 and $x \geq$ or $\leq \frac{U_N}{U_M} \cdot \frac{OA}{2}$

As before fractures occur at positions from the interface equal to half the length of the horizontal intercept line and in the time equal to $\frac{\text{half the length}}{U_M}$, except for the upper fracture of 3,3 intercepts which occurs at the position from the interface equal to half the length of the intercept line, denoted by 'a' and in the time $\frac{b}{U_M} + \frac{a}{2U_M}$ where $\frac{b}{U_M} = \frac{2x}{U_N}$.

The influence of a backing material or liner is therefore to suppress any fracture(s) that should be produced without the backing, either by inhibiting some or all of such fractures or by increasing their lengths but reducing their momenta.

4. The following example illustrates in a quantitative manner the suppressing influence of a backing liner to a plate. The plate is IT 80 armour, shocked by detonation or by the impact of a flying plate. It is assumed that the initial shock intensity is less than 130 kb so that there is none of the complications of induced phase changes. Thus in the vicinity of the interface the shock front is assumed of intensity about 65 kb falling linearly to zero in about 5μ sec($\lambda \sim 25$mm). In this domain of shock the critical fracture stress for IT 80 is roughly 35 kb. The backing materials are those for which their shock properties are known, namely, and perhaps not untypically, perspex and tufnol. Fig 6(b) can therefore be drawn for the three materials involved and the value(s) for point c determined - about 20 kb and 32 kb for perspex and tufnol respectively. (These values can be determined accurately enough in this instance from the well-known stress/impedance expression $\sigma_r = \dfrac{(\rho_M U_M - \rho_N U_M)\,\sigma_C}{\rho_M U_M + \rho_N U_M}$ This enables the fracture locations and spall momenta to be determined, Fig 8. With no backing liner one spall is produced of length (or thickness) of about $\frac{14}{2} = 7$mm. A matching length $x = \frac{U_N}{U_M} \cdot \frac{\lambda}{2}$ of perspex increases the length of spall to about $\frac{20}{2} = 10$mm, the trapped momentum being slightly reduced. A matching length of tufnol completely suppresses fracture and hence spall formation. The matching length (or thickness) of tufnol required for spall inhibition is $x \sim \frac{5.8 \times 25}{5.2 \times 2} \sim 14$mm and less accurately for perspex (since it nearly inhibits) is $x \sim \frac{6.2 \times 25}{5.2 \times 2} \sim 15$mm. A more accurate treatment would take into account the influence of attenuation (incident and reflected rarefactions and lateral release waves) with refinements of rate and time effects in the fracture mechanisms. These refinements would likely lead to thinner spalls and somewhat thinner matching liners as indicated by the arbitrarily drawn (dotted curve) tail to the shock front in the manner also illustrated in Fig 1.

In the above example the backings are seen to inhibit fracture in the one case and to suppress fracture in the other by increasing length and reducing velocity of spall, its momentum not necessarily being greatly affected. In a realistic three-dimensional situation, however, the 'length' or area of fracture usually decreases with increase in its position from the free surface or interface. This follows because of the continued influence of rarefaction and lateral release waves in the longer times involved. Furthermore although fracture may occur, spall detachment cannot unless there is more than sufficient energy in the system to cause circumferential failure by shear, for in this region there is considerable localized strain

and it is only when a critical value of strain is reached that failure occurs. Thus a backing either inhibits fracture altogether or positions fracture such that the mass and velocity characteristics of any spall produced are reduced. The suppressing influence of the backings can of course be redressed by increasing the strength of the incident wave. For example the tufnol backing fails to inhibit fracture when the intensity of the shock is increased to 75 kb (Fig 8).

5. Jet produced shocks and interactions

The simple one-dimensional analyses outlined in the preceding pages are valid for uniform shock propagation in a plane. Plane wave propagation can be fairly accurately attained in flying plate experiments and to a less accurate extent in similar experiments when the source of shock is a detonating charge. In principle the same processes of shock propagation and spalling mechanisms apply to armours in which shock is generated during the penetrative phases of a hollow charge jet; but propagation is not in a plane. Shock is continuously generated and propagated in the manner of that produced by a fast, subsonic moving, detonating charge of long duration. Pictorial representation here is simplified by assuming the jet to be in the form of a long rod which penetrates the armour at constant high velocity. Fig 9 illustrates rod and assumed spherically expanding shock front progress for attack at 45°, and for a 3/5 ratio of penetration to shock velocity. Shocks generated at jet positions 0, 1, 2, 3, 4, 5 are shown for the time the leading front takes to propagate from face to face along the jet axis. The leading front first reaches the rear face when the jet tip is at position 3. It has been well reflected in rarefaction by the time the jet has penetrated to position 5 when the front reaches the rear face directly in line with the jet axis. In the two-dimensional illustration the pressure/distance profile along any line drawn from the jet tip at any time depends on a number of attendant influences; those of rarefaction, radial dissipation and particularly release waves generated at the periphery of the moving interface between rod and plate. Definition and assessment are certainly difficult. Provided the peak intensities are high enough and the angles of incidence with the rear face of the plate are small, there are likely to be at some stage in the reflection within a changing localised region conditions that are favourable to spall production. Thus only when the peak intensity is of sufficient magnitude would spalling be expected in regions at and near normal wave incidence with the rear face. As penetration proceeds it is conceivable that these regions shift towards the line of the jet and that fracture might run in this direction occurring before jet emergence. In line with the jet both the angle of incidence and shock profiles may tend to be unfavourable to spalling. These aspects change with change in angle of jet attack. Furthermore the impact pressures generated are high enough to cause such flow and lateral displacement of material that a cylindrical hole around the rod axis is formed of from about 4 to 6 copper rod diameters in steel. Analysis and assessment become even more difficult if account is taken of the complicated wave formations (negative shocks) but rapid attenuations that occur in armour steels when subject to impact pressures far about 130 kb, as is the case when jets penetrate steel at pressures in the region of 1000 kb (6500 tons/sq in). Detailed analysis of this problem would appear quite feasible by adaptation and extension of the computer codes employed by AWRE in the analysis of the simpler problem of

spalling by intense plane shock propagation in polymorphic materials.

For very thick plates favourable conditions for spalling may not arise until deep penetration has occurred. The wave length to plate thickness ratio for thin plates (less than one rod or jet diameter) probably does not allow for Hopkinson type spalling. The rear face motion imparted to a thin plate is of the order of the jet velocity, moving outwards in the manner of an expanding bubble around the jet tip during the expansion, the tip contributing to material in the bubble front by shock erosion. The bubble of material thins in the expansion and breaks into fragments which are projected in a cone of about 90° solid angle symmetrical about the jet for attack at normal but moving more and more away from the jet axis towards the axis normal to the plate as angle of attack increases. Whilst this form of fragmentation must accompany energetic jet perforations whatever the plate thickness, its contribution to the total fragment projection in general probably decreases as plates increase from thin to thick (within limits), partly because conditions favourable to spalling tend to increase while those for size and energy of bubble decrease. Rear face damage characteristics are illustrated in Fig 9. If not already done it would be of basic interest to carry out one or two experiments directed towards 'identifying' spall and bubble fragments and assessing their relative contributions.

In flying plate, and explosively, induced fracture and spalling the area, mass and velocity of spall decrease as the plate thickness increases. The decrease in velocity follows from the increase in attenuation while the decrease in area is partly due to the fact that the thicker the plate the more the release waves that originate from the peripheral regions of the seat of impact eat into and reduce the effective area of the plane shock. Thus as referred to in Section 4 the addition of a backing to the plate would lead to a reduction in the mass and velocity of spall or scab, and in the limit to its inhibition. Under jet-attack these features in behaviour would also be expected though perhaps less simply in that they might show optimum characteristics in spall behaviour.

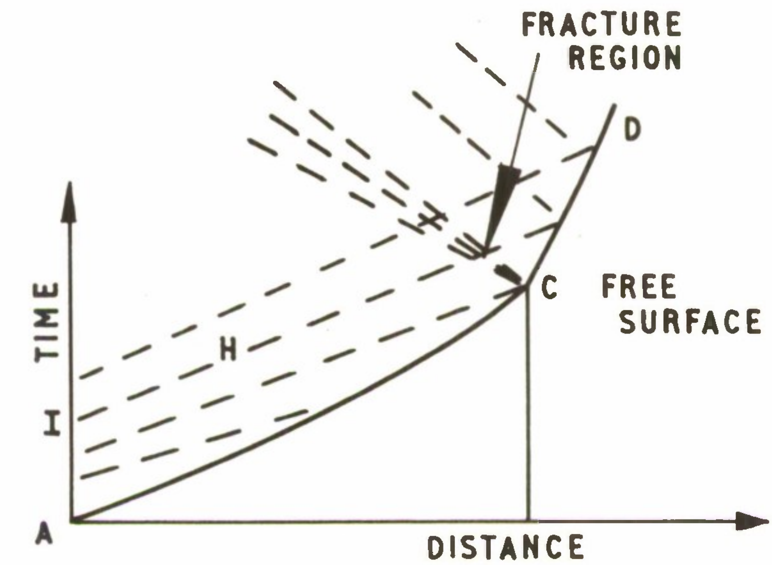
Though no attempt is made here to consider mechanisms of spall break-up, it is easy to see that it must occur in armour under jet attack because of the shears generated by non-uniform shock loading and prevalent rear face incidence at angle. In flying plate and detonating charge experiments the plane shock propagated at normal in the armour leads to a large, usually unbroken spall, in the form of a scab, the sides of which have separated from the parent plate by shear. It is worth mentioning that, even at small angles of plate or detonation impact, Hopkinson type fractures tend to be suppressed and eventually inhibited. The stronger the shock the less the suppression with angle.

6. General comments and proposals

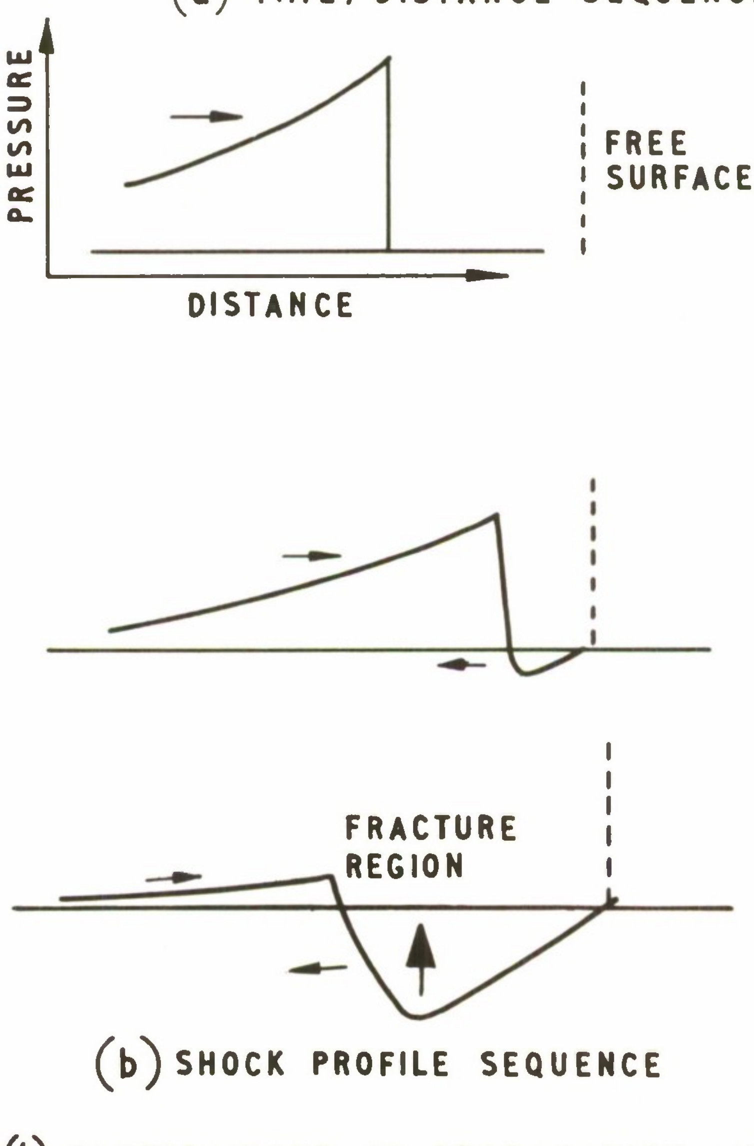
The spall suppressing influence of armour backings has been demonstrated in experiments and presumably in field trials concerned with jet performance by observation of fragment damage beyond the overmatched armour; but it is doubtful whether systematic investigations on these armours have been carried out over the years comparable to those concerned with unbacked armours. The simplified theory in this study may help to ellucidate the main

controlling mechanisms involved in the process of shock propagation, fracture and spalling in armours with particular reference to the suppressing influence on spalling of interfaces, as when the armour plate is backed by a plate of lower shock impedance. On the assumption that backed armours of this kind are likely to be met in combat (particularly because appropriate liner backings to the armour are used as shields against nuclear radiation) it may be a matter of some concern to ask whether it is possible and feasible to reduce or counteract their suppressing influence by appropriate modifications in warhead design. The three suggestions that come to mind designed to redress or counteract the loss in spall fragment performance of backed armours are (a) increase in the size of the hollow charge, (b) modifications in charge liner design and (c) the use of double liners and/or follow-through devices. That suggestion (a) would lead to improved fragmentation follows from consequent increases in shock strengths with considerations of linear scaling relationships between jet and armour as indicated in Section 4. With a few plausible assumptions a rough guide to expected improvement in spall performance from backed armour with linear increase in the size of charge could be obtained by the simplified method of assessment outlined in Section 4 for plane wave propagation. A few well-directed experiments should reveal the extent to which the charge must be increased in size consistent with that acceptable for service use. Suggestion (b) is more doubtful of achieving desired performance, for a change in liner design in a charge of 'fixed' dimensions would mean that the jet must change in its properties of length, diameter and velocity gradient so that the shocks generated during the changed penetration must change. But since the charge is not altered significantly in size and an acceptable degree of jet overmatch must be retained, the likely small changes in shock characteristics would lead, if at all, only to marginal increases in spall fragment performance, and this would need to be balanced against the loss in residual jet damage by the reduced overmatch. A few directed experiments might indicate the likelihood of any worthwhile improvement. Suggestion (c) is based on the after-burning performance of Cu/Al or Cu/Mg jets of penetrative capability found to be only a little less than a corresponding copper jet. The suppressing influence of a backing on fragment lethality might at least be partly compensated by the after-burning blast and smoke effects, which would need to be assessed by trials. Research into the after-burning and smoke potential of jets from liners made of superplastic alloys of Cu/Mg/90/10 and Sn/Pb/60/40 might be of value here. Similarly, follow-through devices, if found practically feasible, could clearly offset losses in fragment performance.

No mention has been made in this study of the spalling and fragmentation of backing materials, which must occur in the process of shock interactions. Though backings suppress spalling in the armour plate their own spalling and break-up must contribute to damage beyond, the lethal aspect of which should not be ignored but should be assessed by trials.

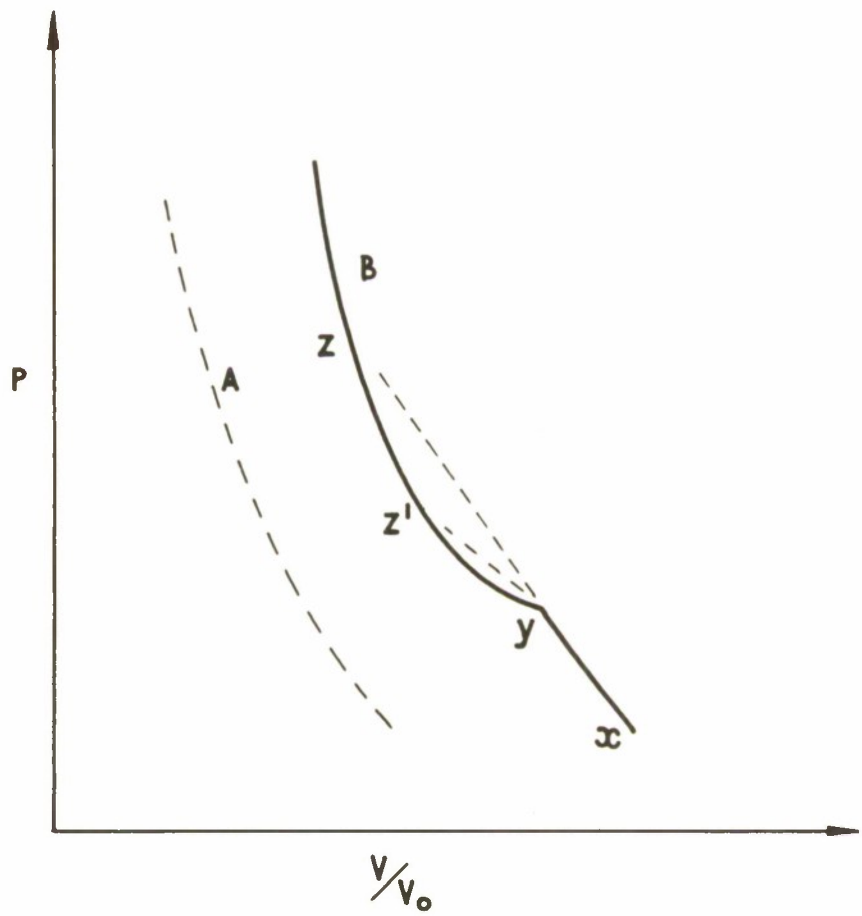


(a) TIME/DISTANCE SEQUENCE



(b) SHOCK PROFILE SEQUENCE

FIGS. 1 (a)(b) ILLUSTRATIONS OF PROPAGATION AND FRACTURE IN SINGLE PHASE MATERIALS

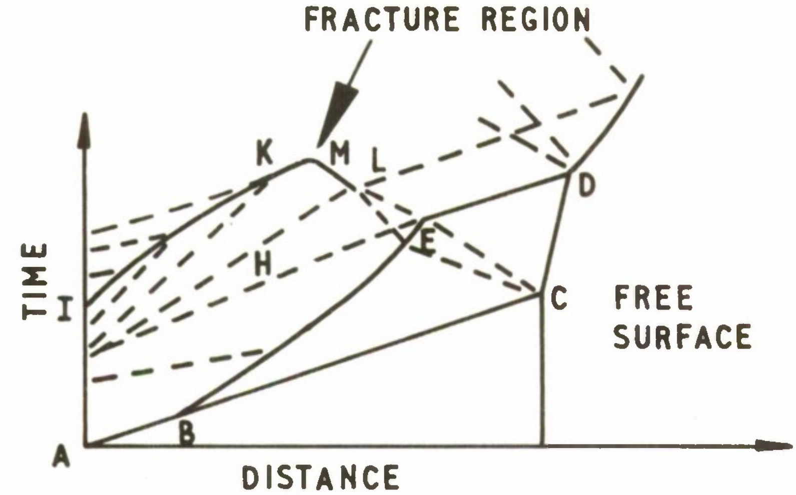


CURVE A : SINGLE PHASE MATERIAL (e.g. BRASS)
CURVE B : SHOCK INDUCED PHASE CHANGE IN POLYMORPHIC MATERIAL (e.g. MILD STEEL, IT80)

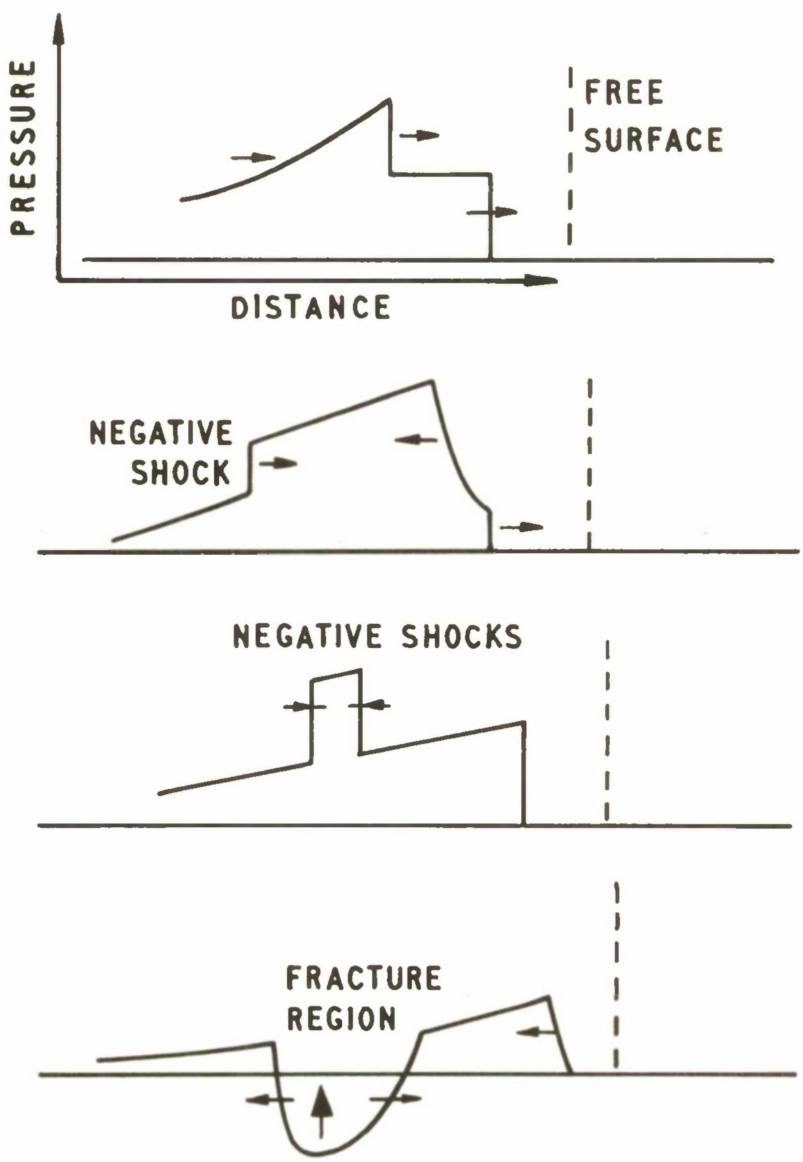
FIG. 2 REPRESENTATIVE HUGONIOT CURVES

CONFIDENTIAL

FIGS.3(a)(b)



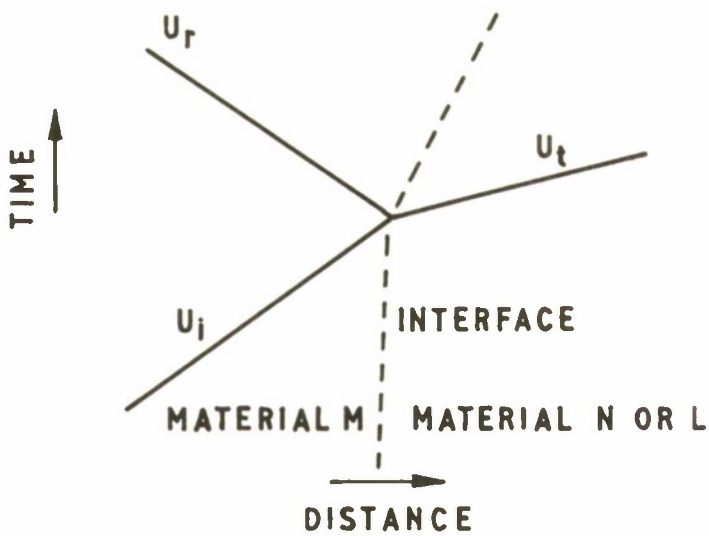
(a) TIME / DISTANCE SEQUENCE



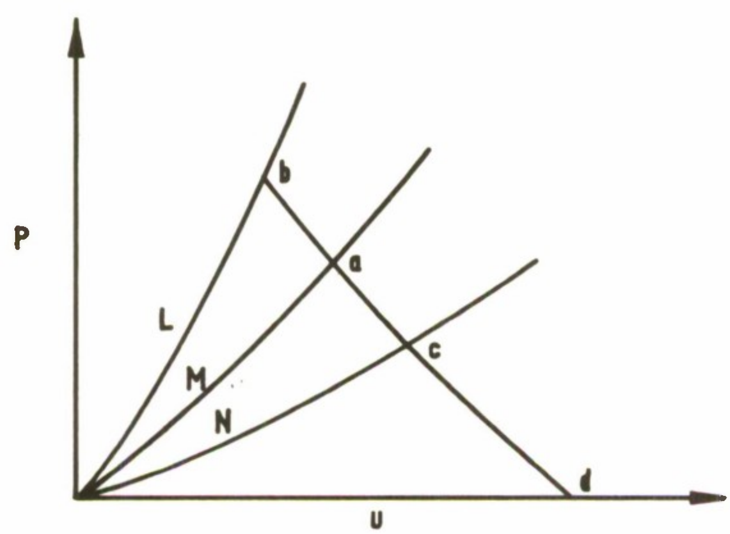
(b) SHOCK PROFILE SEQUENCE

FIGS.3 (a) (b) ILLUSTRATIONS OF PROPAGATION AND FRACTURE IN POLYMORPHIC MATERIALS

CONFIDENTIAL



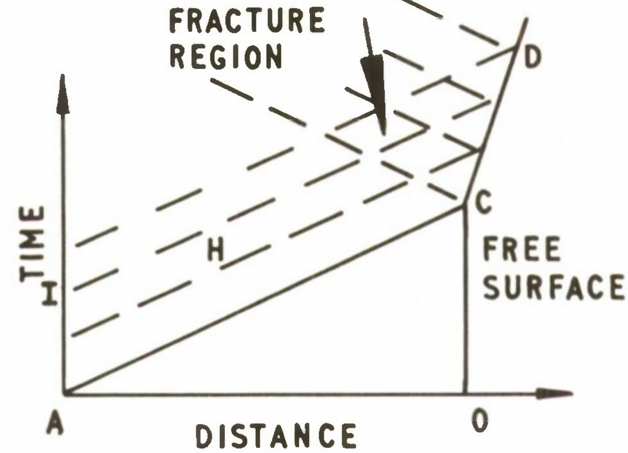
(a) TIME/DISTANCE SEQUENCE OF INCIDENT, REFLECTED AND TRANSMITTED WAVES



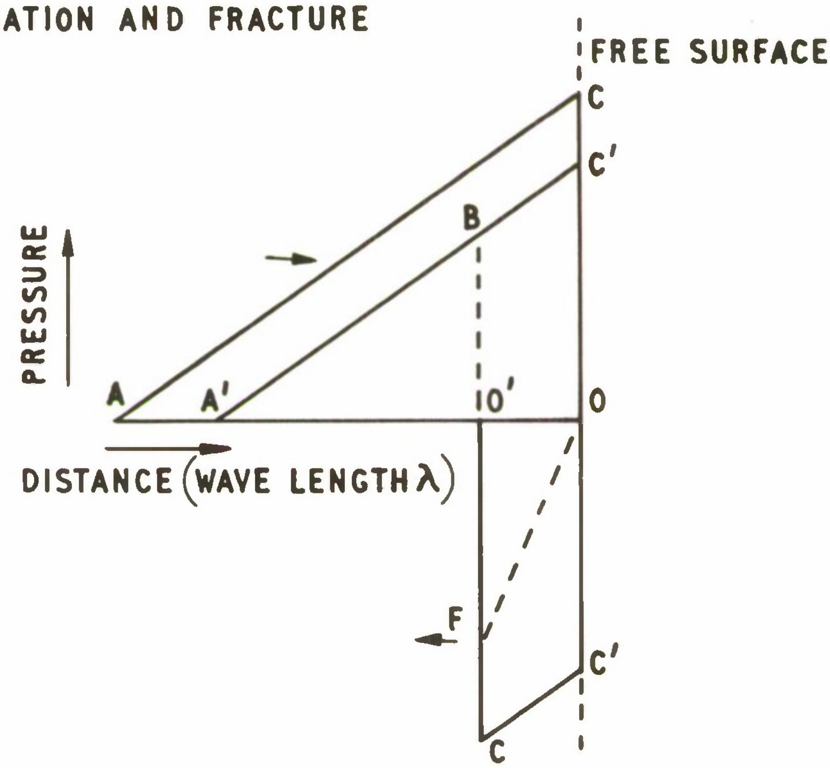
(b) PRESSURE/PARTICLE VELOCITY RELATIONSHIPS FOR THREE MATERIALS L,M,N, ILLUSTRATING INTERFACE WAVE CHARACTERISTICS BETWEEN M AND L AND M AND N

FIGS. 4(a)(b) SHOCK PROPAGATION CHARACTERISTICS ACROSS INTERFACES

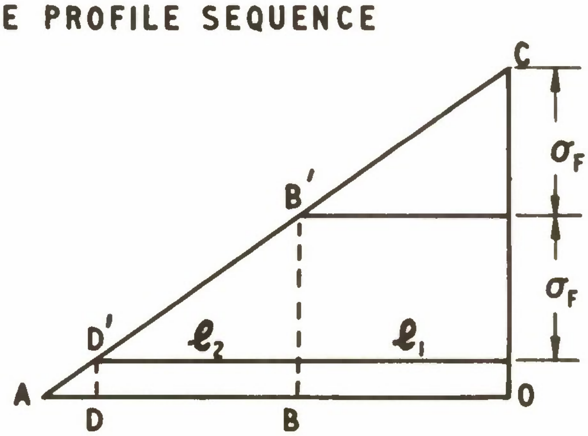
FIGS. 5(a)(b)(c)



(a) TIME / DISTANCE SEQUENCE OF NON-ATTENUATING WAVE PROPAGATION AND FRACTURE

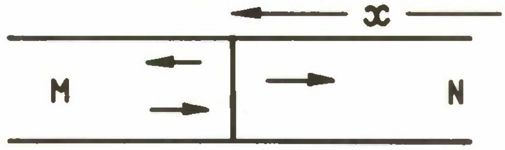


(b) WAVE PROFILE SEQUENCE

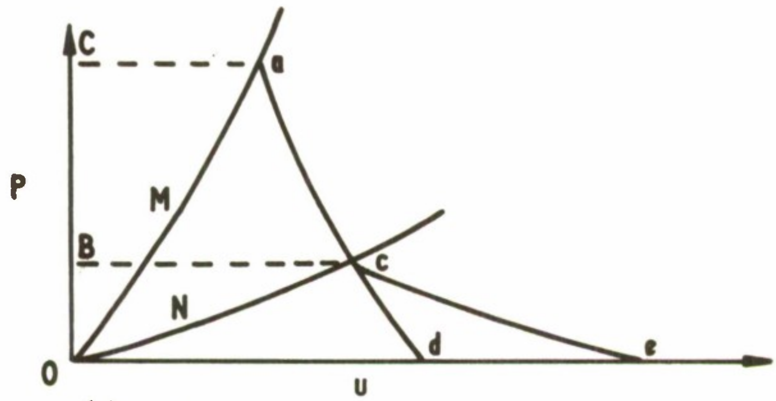


(c) DETERMINATION OF NUMBER AND LOCATION OF FRACTURES

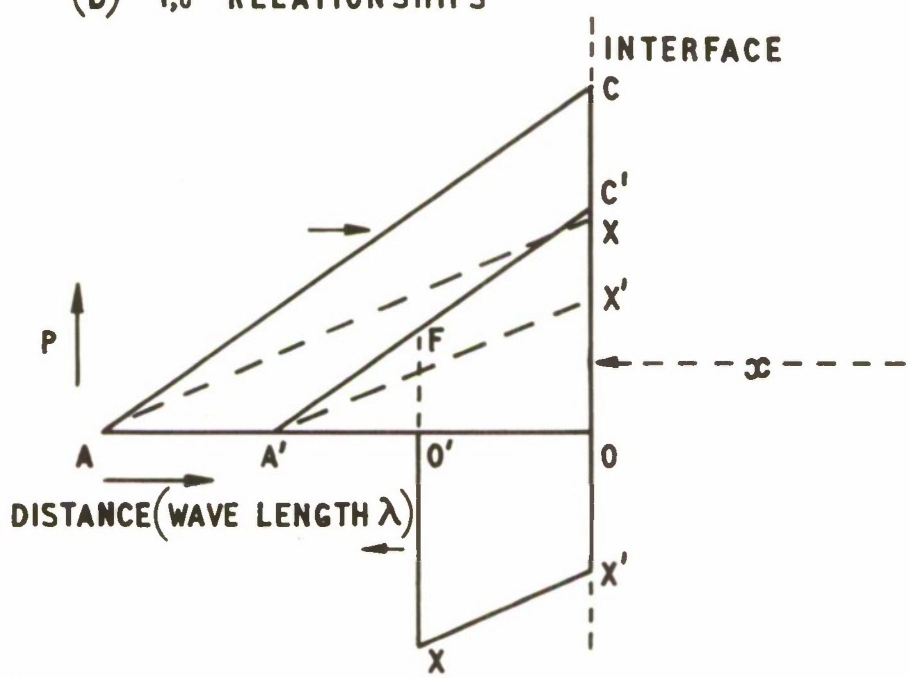
FIGS. 5 (a)(b)(c) ILLUSTRATIONS OF SIMPLIFIED WAVE PROPAGATION, FREE SURFACE REFLECTION AND FRACTURE



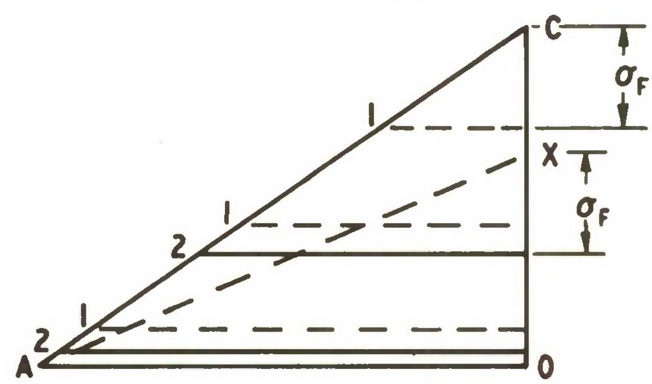
(a) PROPAGATION ACROSS M/N INTERFACE $\left(x \geqslant \frac{U_N}{U_M} \cdot \frac{\lambda}{2}\right)$



(b) P,U RELATIONSHIPS



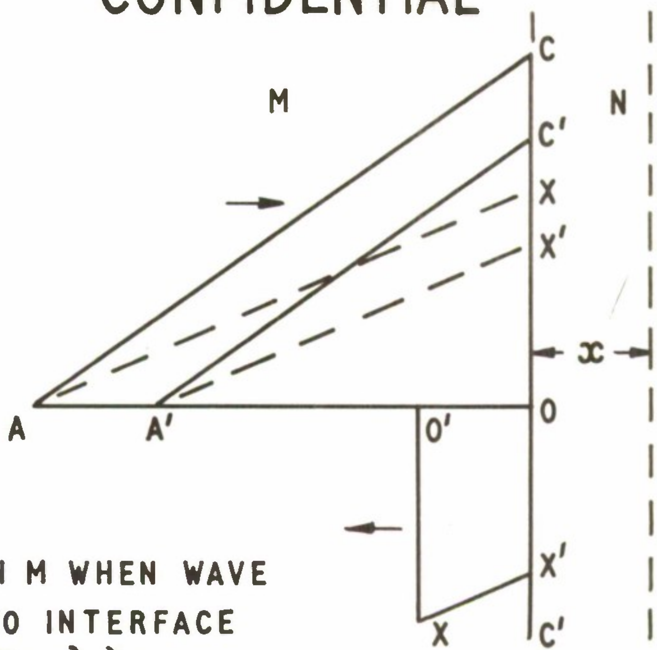
(c) WAVE PROFILE SEQUENCE AND FRACTURE



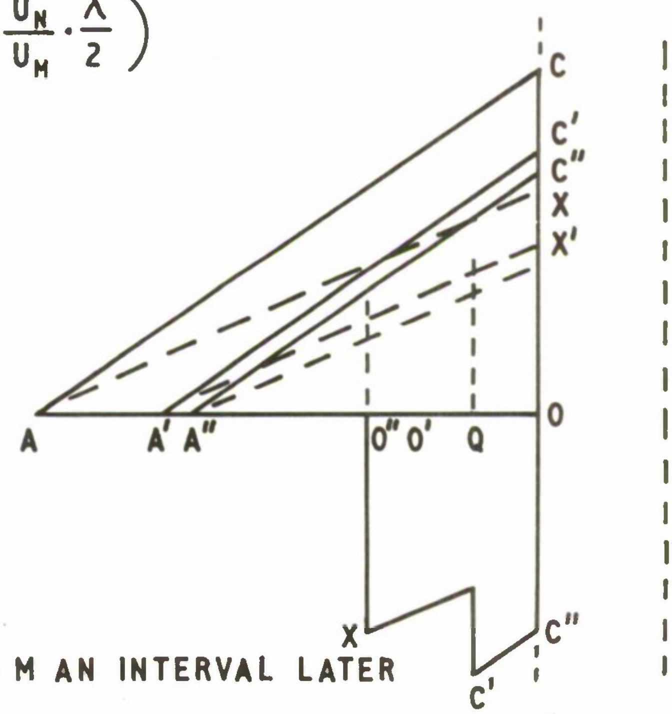
(d) DETERMINATION OF NUMBER AND LOCATION OF FRACTURES

FIGS. 6 (a)(b)(c)(d) ILLUSTRATIONS OF SIMPLIFIED WAVE PROPAGATION, INTERFACE REFLECTION AND TRANSMISSION, AND FRACTURE

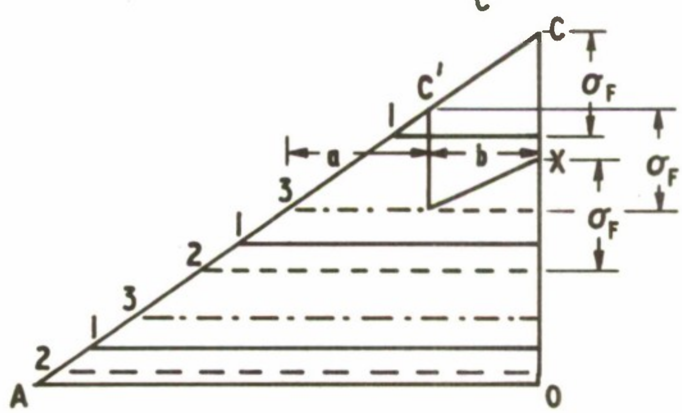
FIGS.7(a)(b)(c)



(a) WAVE PROFILE IN M WHEN WAVE IN N RETURNS TO INTERFACE $\left(x \leqslant \frac{U_N}{U_M} \cdot \frac{\lambda}{2} \right)$



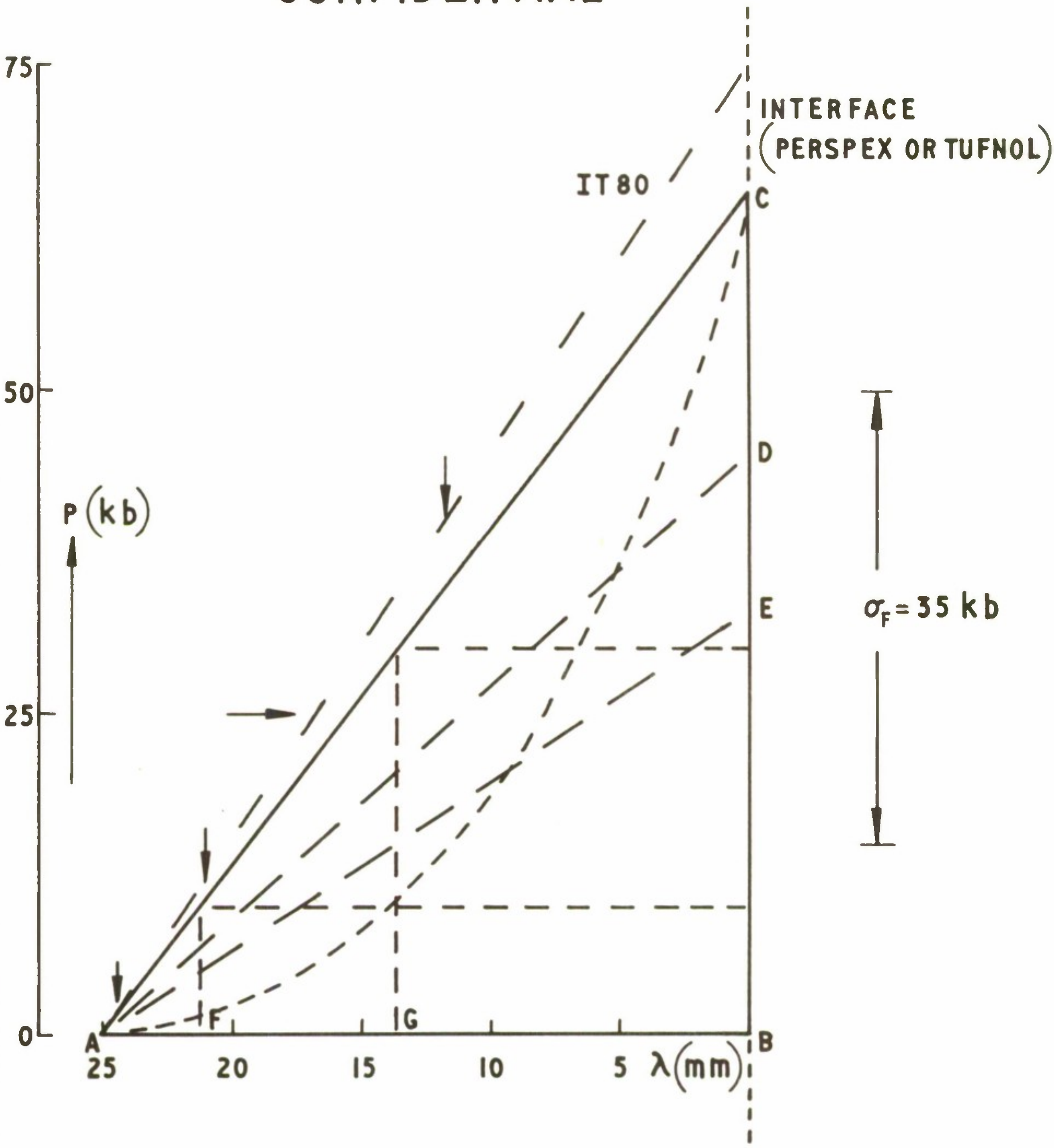
(b) WAVE PROFILE IN M AN INTERVAL LATER



(c) DETERMINATION OF NUMBER AND LOCATION OF FRACTURES

FIGS.7(a)(b)(c) ILLUSTRATIONS OF SIMPLIFIED WAVE PROPAGATION, INTERFACE REFLECTION AND TRANSMISSION, AND FRACTURE

FIG.8



ABC NON-ATTENUATING INCIDENT WAVE
ABD TENSION WAVE REFLECTED FROM IT80/PERSPEX INTERFACE
ABE " " " " IT80/TUFNOL "

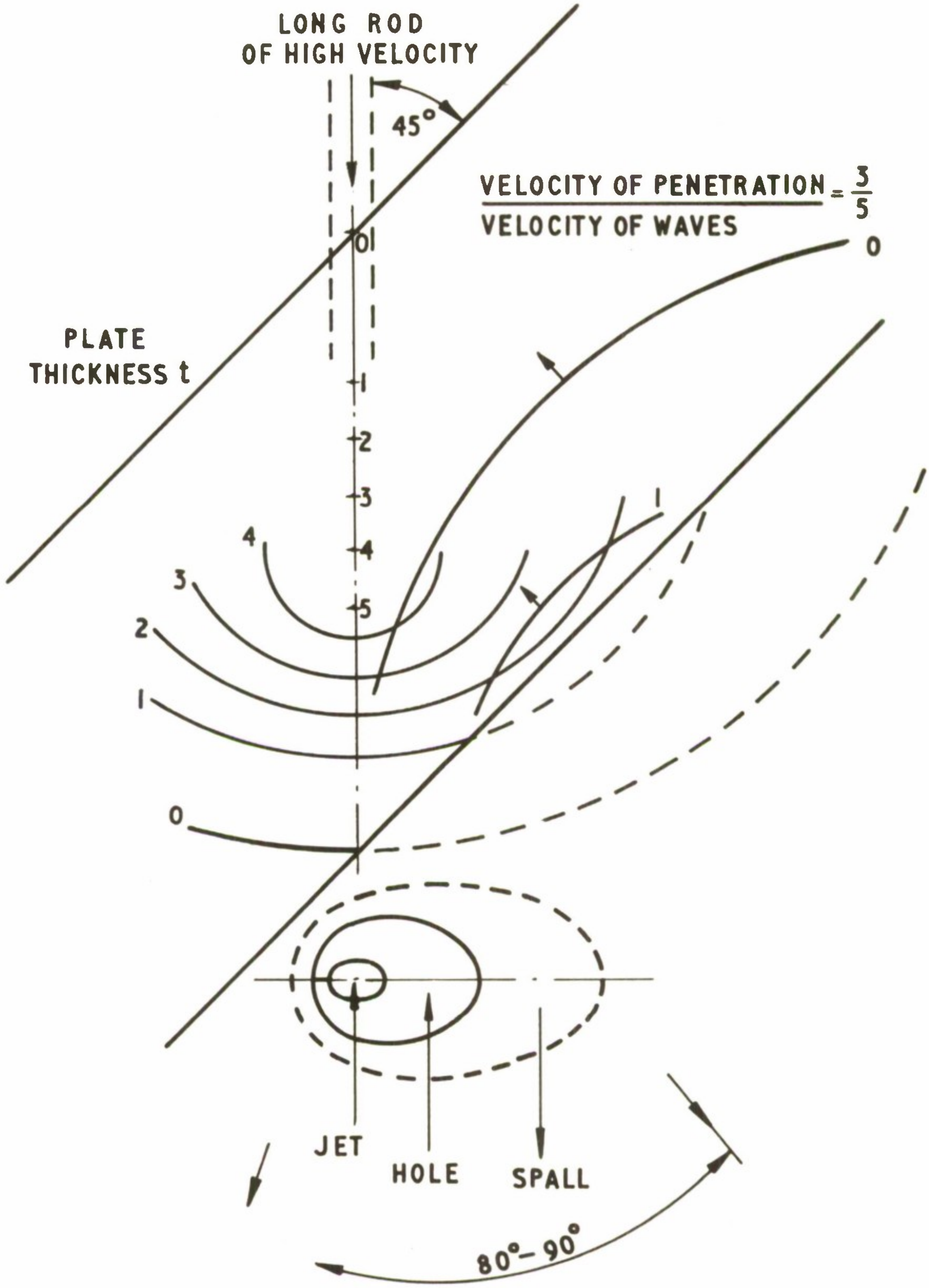
GB TWICE SPALL LENGTH FOR NO BACKING
FB " " " " PERSPEX "

NO FRACTURE FOR TUFNOL BACKING

ABC DOTTED LINE: ATTENUATING INCIDENT WAVE (ARBITRARILY DRAWN)

FIG. 8 INFLUENCE OF PERSPEX OR TUFNOL BACKING ON FRACTURE IN IT80 ARMOUR

FIG.9



SPHERICALLY EXPANDING WAVE FRONTS GENERATED AT VARIOUS STAGES IN THE PENETRATIVE PHASE AND IN TIME $T = \frac{t \sec \theta}{U} = \frac{\sqrt{2}t}{U}$

PICTORIAL REPRESENTATION OF REAR FACE DAMAGE CHARACTERISTICS (NOT TO SCALE)

FIG. 9 HIGH VELOCITY ROD (OR JET) ATTACK AT 45°

CONFIDENTIAL

Ministry of Defence
Royal Armament Research and Development Establishment
RARDE Memorandum 33/72

623.562.3:
623-91:
678.026.3:
623.452.31:

The spalling of armour plate and the influence of backing liners (title RESTRICTED)

W M Evans

November 1972

This note examines theoretically the influence of backing liners, such as Perspex and Tufnol, on the spalling of armour plate under attack, particularly by hollow-charge jets. Very little supporting experimental work has been undertaken but the report suggests that relatively thin liners can significantly reduce or suppress spalling, with consequent reduction in behind-plate lethality. (If the liners are thick, a further reduction in lethality by spall absorption in the backing material can occur; this is not analysed in the note).

CONFIDENTIAL

CONFIDENTIAL

Ministry of Defence
Royal Armament Research and Development Establishment
RARDE Memorandum 33/72

623.562.3:
623-91:
678.026.3:
623.452.31:

The spalling of armour plate and the influence of backing liners (title RESTRICTED)

W M Evans

November 1972

This note examines theoretically the influence of backing liners, such as Perspex and Tufnol, on the spalling of armour plate under attack, particularly by hollow-charge jets. Very little supporting experimental work has been undertaken but the report suggests that relatively thin liners can significantly reduce or suppress spalling, with consequent reduction in behind-plate lethality. (If the liners are thick, a further reduction in lethality by spall absorption in the backing material can occur; this is not analysed in the note).

CONFIDENTIAL

CONFIDENTIAL

Ministry of Defence
Royal Armament Research and Development Establishment
RARDE Memorandum 33/72

623.562.3:
623-91:
678.026.3:
623.452.31:

The spalling of armour plate and the influence of backing liners (title RESTRICTED)

W M Evans

November 1972

This note examines theoretically the influence of backing liners, such as Perspex and Tufnol, on the spalling of armour plate under attack, particularly by hollow-charge jets. Very little supporting experimental work has been undertaken but the report suggests that relatively thin liners can significantly reduce or suppress spalling, with consequent reduction in behind-plate lethality. (If the liners are thick, a further reduction in lethality by spall absorption in the backing material can occur; this is not analysed in the note).

CONFIDENTIAL

CONFIDENTIAL

Ministry of Defence
Royal Armament Research and Development Establishment
RARDE Memorandum 33/72

623.562.3:
623-91:
678.026.3:
623.452.31:

The spalling of armour plate and the influence of backing liners (title RESTRICTED)

W M Evans

November 1972

This note examines theoretically the influence of backing liners, such as Perspex and Tufnol, on the spalling of armour plate under attack, particularly by hollow-charge jets. Very little supporting experimental work has been undertaken but the report suggests that relatively thin liners can significantly reduce or suppress spalling, with consequent reduction in behind-plate lethality. (If the liners are thick, a further reduction in lethality by spall absorption in the backing material can occur; this is not analysed in the note).

CONFIDENTIAL

CONFIDENTIAL

Experimental work is needed to optimise this type of improved composite armour. The report also indicates possible warhead modifications to combat such improvements.

9 pp 9 figs

CONFIDENTIAL

CONFIDENTIAL

Experimental work is needed to optimise this type of improved composite armour. The report also indicates possible warhead modifications to combat such improvements.

9 pp 9 figs

CONFIDENTIAL

CONFIDENTIAL

Experimental work is needed to optimise this type of improved composite armour. The report also indicates possible warhead modifications to combat such improvements.

9 pp 9 figs

CONFIDENTIAL

CONFIDENTIAL

Experimental work is needed to optimise this type of improved composite armour. The report also indicates possible warhead modifications to combat such improvements.

9 pp 9 figs

CONFIDENTIAL

AUG 3 1 1973

U.K. CONFIDENTIAL

CONFIDENTIAL

[dstl]

Information Centre
Knowledge Services
[dstl] Porton Down,
Salisbury
Wilts
SP4 0JQ
Tel: 01980-613753
Fax 01980-613970

Defense Technical Information Center (DTIC)
8725 John J. Kingman Road, Suit 0944
Fort Belvoir, VA 22060-6218
U.S.A.

AD#: 596288
Date of Search: 12 December 2006

Record Summary:
Title: The spalling of armour plate and the influence of backing liners
Covering dates 1972 Nov 01 - 1972 Nov 30
Availability Open Document, Open Description, Normal Closure before FOI Act: 30 years
Former reference (Department) RARDE Memorandum 33/72
Held by The National Archives, Kew

This document is now available at the National Archives, Kew, Surrey, United Kingdom.

DTIC has checked the National Archives Catalogue website (http://www.nationalarchives.gov.uk) and found the document is available and releasable to the public.

Access to UK public records is governed by statute, namely the Public Records Act, 1958, and the Public Records Act, 1967.
The document has been released under the 30 year rule.
(The vast majority of records selected for permanent preservation are made available to the public when they are 30 years old. This is commonly referred to as the 30 year rule and was established by the Public Records Act of 1967).

This document may be treated as UNLIMITED.